A BLAST-WAVE MODEL FOR THE EXPLOSION IN THE GALAXY M82*

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I. INTRODUCTION

The radio and optical data pertaining to M82 were reviewed in a previous paper (Solinger 1969; hereinafter referred to as "Paper I"). It was shown that the polarized optical continuum detected at distances as far as 5′ (approximately 5 kpc) from the center of the galaxy is probably not due to synchrotron radiation and that the lines observed are probably excited collisionally, not radiatively as previously supposed. Moreover, these data were shown to provide a basis for consideration of a new model for the explosion; the energy released gives rise to a shock wave and consequent hydrodynamic flow which propagates through the galactic and circumgalactic media. The heating and compression which accompany the shock provide the line-excitation mechanism. The polarization pattern observed can be accounted for by postshock Thomson scattering of light from an unobserved, optically bright, central nucleus. The nucleus, probably obscured by dust, has been estimated to be of about the brightness of a Seyfert nucleus.

II. THEORY OF THE EXPLOSION

Our approach to constructing a model is the following. First, we investigate the kind of hydrodynamic flow associated with the release of a large amount of energy over a very short time and in a very small volume. While other models for the energy release are possible, this is the simplest assumption to make. Next, we use the density distribution to construct a Thomson scattering atmosphere behind the shock. Finally, we compare the predicted Stokes-parameter distribution with the data and determine the various parameters of the model.

a) Sedov Solutions

If we neglect gravity, magnetic effects, all radiative energy losses, asymmetries, and counterpressure, and assume the energy release to be instantaneous at a point in a medium for which the ambient density is given by $\rho_0 = A/r^\omega$, then a self-similar solution can be found (Sedov 1959). The solution is completely characterized by the parameters A, ω, E_0 (the energy released), and γ (the ratio of specific heats, taken to be $\frac{5}{3}$). The solution will thus depend on the dimensionless variable

$$\lambda = r \left(\frac{aA}{E_0 t^2}\right)^{1/(5-\omega)} , \qquad (1)$$

where a is a numerical constant inserted to ensure $\lambda = 1$ at the shock front. Then the shock radius is given by

$$R_s = (E_0 t^2 / aA)^{1/(5-\omega)} . \qquad (2)$$

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* [The full-length paper, of which this Letter is a short summary, was originally submitted on 1969 February 7. By a series of unfortunate accidents, the publication of this paper has been overly delayed. But M82 continues to be an object of great interest theoretically and observationally. On this account, this summary of the paper is published herewith.—EDITOR.]

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This means that $\lambda = r/R_s$. The velocity of the shock is

$$u = \frac{dR_s}{dt} = \frac{2}{5-\omega}\frac{R_s}{t} . \tag{3}$$

We denote the Sedov solutions by

$$N_e = N_s n_\omega(\lambda) , \quad T_e = T_s t_\omega(\lambda) , \quad V = V_s v_\omega(\lambda) , \tag{4}$$

where N_e (T_e, V) is the electron density (temperature), and the subscript s indicates evaluation at the shock front. In terms of the parameters to be determined, T_s is given by

$$T_s = \frac{3m_H}{8k(5-\omega)^2}\frac{R_s^2}{t^2} . \tag{5}$$

Since $V_\omega \sim r$ for all ω, the velocity field observed does not serve to differentiate between models.

b) The Stokes Parameters

Taking the nuclear luminosity to be L and assuming the optical depth $\tau_t \ll 1$, we find that the Stokes parameters of the scattered light are given by

$$Q(\lambda,\omega) = \sigma \int \frac{L}{4\pi r^2}(1 - \cos^2\theta)N_e dz \equiv I_s^0 q_\omega(\lambda) ,$$

$$I^s(\lambda,\omega) = \sigma \int \frac{L}{4\pi r^2}(1 + \cos^2\theta)N_e dz \equiv I_s^0 i_\omega^s(\lambda) , \tag{6}$$

$$U(\lambda,\omega) = V(\lambda,\omega) = 0 , \quad I_s^0 \equiv \frac{\sigma L N_s}{2\pi R_s} ,$$

where $\sigma = \frac{1}{2}(e^2/mc^2)^2$, and the integral is along the line of sight through the shock at a distance $h = \lambda R_s$ from the explosion center. The dimensionless functions $q_\omega(\lambda)$ are plotted in Figure 1 for $\omega = 0, 1.1, 1.5, 1.8$, and 2.001.

To I^s we must add the contribution from free-free emission behind the shock. This is given by (Allen 1963) as

$$I^b(\lambda,\omega) = \int C_b N_e T_e^{-1/2} dz \equiv I_b^0 i_\omega^b(\lambda) , \tag{7}$$

where $C_b = 5.4 \times 10^{-39} \times \Delta\nu_{op} = 1.6 \times 10^{-24}$, and $I_b^0 = 2C_b N_s T_s R_s$.

The total predicted intensity is thus

$$I_\omega^t = I_\omega^b + I_\omega^s = I_0^s[i_\omega^s(\lambda) + \beta i_\omega^b(\lambda)] , \tag{8}$$

where $\beta = I_b^0/I_s^0$. Since there may be other sources of light (e.g., line emission), we can establish only an upper limit for β, once I_s^0 is determined.

c) Results

Comparing $Q(\lambda,\omega)$ with the data, we find that a fit can be made only for $\omega = 1.8$ (Fig. 2). From this we determine $R_s = 300''$ (5 kpc) and $I_s^0 = 1.6 \times 10^{-15}$ erg cm^{-2} sec^{-1} per square second of arc. I_s^0 can be determined only to within about a factor of 2. The time since the explosion is determined by comparing the theoretical formula good near the center,

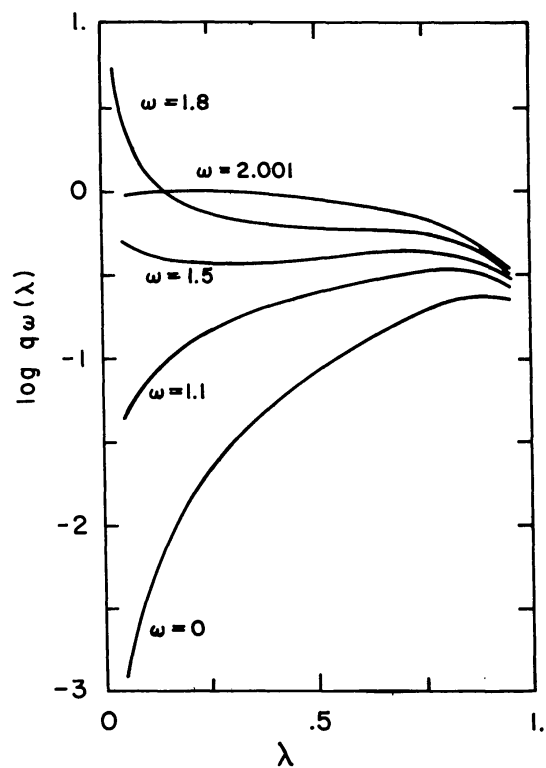$$V = \frac{2}{\gamma(5-\omega)}\frac{r}{t} , \tag{9}$$
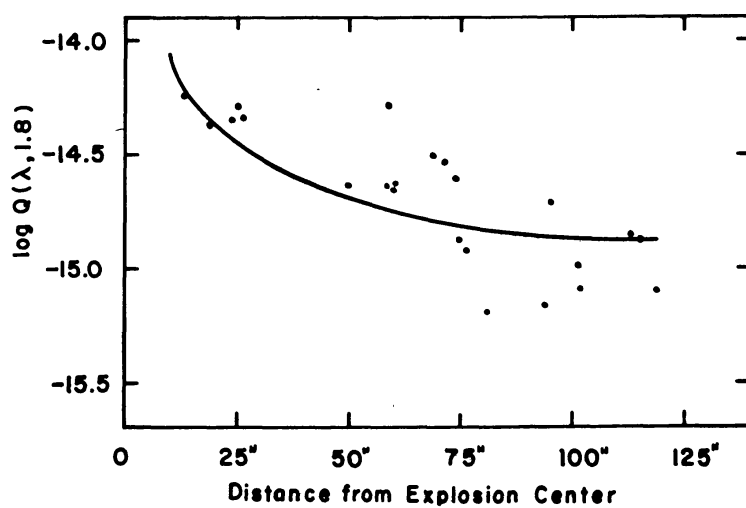
Fig. 1.—The dimensionless polarized intensity functions

Fig. 2.—Fit of $Q(\lambda,1.8)$ to the data

with the empirical relation (see Paper I)

$$V = \mu' r \,.\tag{10}$$

We obtain $t = 5 \times 10^5$ years. Finally, β is established by comparing the predicted and observed intensity far from the center where there is unlikely to be a stellar component. Since Hoag (1963) has found appreciable hydrogen emission at distances of $130''$ from the galactic center, the value of β determined in this way must be regarded as an upper limit. Thus $\beta \le 7.5$.

The determination of these parameters allows us to determine the quantities N_s, L, E_0:

$$N_s = 5.1\beta^{1/2} \, \text{cm}^{-3} \,, \quad L = 3.2 \times 10^{43}\beta^{-1/2} \, \text{ergs sec}^{-1} \,, \quad E_0 = 2.1 \times 10^{60}\beta^{1/2} \, \text{ergs}. \tag{11}$$

A lower limit to β follows from noting that no Seyfert nucleus has a luminosity greater than about 10^{44} ergs sec^{-1}. Thus $\beta > 0.1$, and we obtain[1]

$$1.6 \le N_s \le 14 \, \text{cm}^{-3} \,, \quad 1.2 \times 10^{43} \le L \le 10^{44} \, \text{ergs sec}^{-1} \,,$$
$$6 \times 10^{59} \le E_0 \le 6 \times 10^{60} \, \text{ergs}. \tag{12}$$

d) M82 as an X-Ray Source

The temperatures predicted behind the shock are of the order of $10^{8\,\circ}$ K. Thus X-ray bremsstrahlung is expected. Assuming no absorption, the total flux in the 2–8 Å range has been calculated to be

$$F^{\text{M82}} = 6.9\beta \, \text{keV cm}^{-2} \, \text{sec}^{-1} \,. \tag{13}$$

The corresponding flux from Sco X-1, calculated from the data of Peterson and Jacobson (1966), is

$$F^{\text{Sco}} = 200 \, \text{keV cm}^{-2} \, \text{sec}^{-1} \,;$$

thus

$$0.025 \le F^{\text{M82}}/F^{\text{Sco}} \le 0.25 \,, \tag{14}$$

and a measurement would determine the last parameter.

e) Infrared Observations[2]

The inferred high optical luminosity of the hypothesized nucleus warrants the speculation that it may be observable in the infrared. For example, if it is as bright as the source in NGC 1068 (Pacholczyk and Wisniewski 1967), then, taking the distance to that galaxy to be 16 Mpc (Burbidge, Burbidge, and Prendergast 1959), M82 should be about 30 times as bright. Thus, even if the nucleus were considerably less luminous, it would be detectable in the infrared.

III. CONCLUSIONS

It has been shown that a blast-wave interpretation of the explosion in M82 provides a quantitative basis for understanding the observed features. Self-similar solutions to the equations of hydrodynamics for an explosion in a medium with a power-law-varying density, together with the hypothesis of a bright optical nucleus, yield a reasonable fit to the polarized intensities observed and allow all parameters except one to be deter-

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[1] The luminosity of the "nuclear region" has recently been measured photoelectrically for the interval λλ3500–11000 by Peimbert and Spinrad (1969 preprint) and is found to be 4.4×10^{43} ergs sec^{-1}.

[2] This is the original speculation, proposed as early as 1967 (Solinger 1967). Although an infrared nucleus has recently been observed, the author feels warranted to leave it in this form.

mined. It should be stressed here that no a priori assumption of the electron density or nuclear luminosity has been made; these are free parameters determined solely by the fit of the predicted quantities to the data. An upper limit to the undetermined parameter is established, and a lower limit has been devised in keeping with the spirit of the model. The relevant results are summarized in Table 1. The determined quantities are subject to the large errors inherent in any such idealization as the model developed here; the assumption of symmetry neglects effects introduced by the galactic disk, and the assumed power-law density distribution is unlikely, as is the instantaneous release of energy. Nonetheless, the numbers determined serve as guidelines. For example, while the mass determined from the model is about 10^{10} $M\odot$, it may, according to a discussion to be published, be as low as 10^8 $M\odot$. If this is so, then the energy would have to be correspondingly decreased and the densities increased, etc.

The undetermined parameter will be established by an X-ray observation. Such an observation is not necessarily a test of the model, however, since one might have predicted M82 to be an X-ray source simply on the basis of its explosion. An observational

TABLE 1

PARAMETERS DETERMINED BY THE MODEL

Parameter	Value Determined
Electron density:	
Behind shock....................	$1.6 \lesssim N_s \lesssim 14$ cm^{-3}
In filaments....................	$1.3 \lesssim N_f \lesssim 3.6$ cm^{-3}
Between filaments...............	$0.3 \lesssim N_e \lesssim 2.8$ cm^{-3}
Electron temperature:	
Behind shock....................	$T_s = 3 \times 10^8$ ° K
In filaments....................	2×10^7 ° K $\lesssim T_f \lesssim 9 \times 10^7$ ° K
Between filaments...............	$T_e = 10^8$ ° K
Shock radius.....................	$R_s = 5$ kpc $(300'')$
Total energy.....................	$6 \times 10^{59} \lesssim E_0 \lesssim 6 \times 10^{60}$ ergs
Age of explosion.................	$t = (5 \pm 1.5) \times 10^6$ years
Optical luminosity of nucleus.......	$1.2 \times 10^{43} \lesssim L \lesssim 10^{44}$ ergs sec^{-1}
X-ray luminosity (2–200 keV).......	$10^{50} \lesssim L_{XR} \lesssim 10^{52}$ keV sec^{-1}
Mass in blast wave................	$10^8 \lesssim M \lesssim 10^{11}$ $(M\odot)$

test is nevertheless proposed from which positive results can be taken as unique to this model, namely, the constancy of the ratio of polarized intensities in different colors over the entire region outside the disk.

The energy present in the radio source in M82 in the form of relativistic electrons has been estimated at about 10^{53} ergs (Kellermann 1966). Compared to the total energy of the explosion found here, this is a minute amount. This raises the question of the energy requirements of all radio sources. If M82 is typical, then the energies involved in the stronger extragalactic radio sources must be many decades higher than is generally assumed. If not, then M82 is a very anomalous galaxy indeed.

We concluded previously that M82 should be regarded as a Seyfert-like galaxy, seen edge-on. This eliminates two incongruities associated with this galaxy—those of its being the the only radio irregular and the only exploding irregular. The bright optical nucleus is obscured by a dust lane; however, it may be observable in the infrared. This study tends to support these conclusions.

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